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Exploring Earth-Building Technology for Liberia.

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Exploring Earth-Building Technology for Liberia

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ABSTRACT

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This paper discusses earth as a building material and the extent to which earth building technology has evolved over the years. In particular it addresses the adobe, compressed and rammed earth techniques of earth building as suitable techniques for Liberia consumption. In addition, the paper investigates the suitability of the Latosols soils of Liberia for earth building construction purposes using standardized earth building principles and requirements. A local Johnson City, Tennessee, earth sample found to have the same physical characteristics of the Latosols of Liberia was used to simulate Liberia soils to produce specimen blocks at different configurations of moisture content and stabilizers (Bentonite and cement). Following 14 days of cure, the blocks were tested for compressive strength. It was found that blocks produced from the natural soil with no stabilizer added were structurally adequate for building construction purposes. A cost-benefit analysis involving blocks with and without stabilizer (cement) added was also performed.

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CHAPTER 1

INTRODUCTION

Housing – A Complex Asset

Housing is very important to the growth, development, and security of any nation. It bridges livelihood, health, security, education, and social-family stability but is also vulnerable, making it a complex asset. Housing socially binds family and friends and is a basis for pride and cultural identity. In addition, housing is a sign of great economic and political importance. While all these are good attributes of housing, it is also worth mentioning, that housing is an extremely fragile asset. The destruction or loss of homes, in whatever form or manner, is the visible effect of conflict or natural disaster.

Feeling physically deprived is not the only effect from the loss of a home, but it also involves the loss of dignity, identity, and privacy. The loss of home can cause trauma; it causes one to challenge the perception of cultural identity and acceptable social behaviors. The loss of homes also threatens economic growth and national security. On the other hand, when housing is available, the results are resistance to the temptations of conflict and the promotion of reconciliation. Housing ownership increases pride and self-esteem and enables people who are affected by conflict to look forward and invest in their future (Barakat, 2003).

Countless numbers of modern and traditional homes were destroyed or damaged by rival fighting involved with the Liberian civil war – a war that lasted for more than a decade. The destruction and damaging of homes, coupled with the indiscriminate killings of innocent people that characterized the war, forced hundreds of thousands of people into displacement within and outside the country. The war is now over, and the national government is expected to undertake the reconstruction of the country's lost infrastructures and resettle returning and homeless populations. The rate at which citizens and other residents are returning from their places of refuge makes it compelling for the government to act swiftly to accelerate the rebuilding process. Doing so with certainty requires the government and its international partners to do two things: first, they must improve the purchasing power of the people by creating well-paying jobs, and second, they must develop a rather cost friendly and technically sound method of home construction.

The second thing that government and partners must do is what this paper is all about. One way to achieve this part is to do like other governments around the world are doing to progressively and rapidly meet the growing shelter needs of their people. That is, by revitalizing and finding innovative ways to expand the uses of the oldest and abundantly available building material, “Mother Earth.” For example, the people of Nigeria are currently using local earth material to drive their massive building campaign, having failed on many occasions using other approaches (Kabiro, 2005).

Until recent years, most people in Africa and other parts of the world have associated earth-homes with poverty. This is partly so because too often the material is poorly used to allow a progressive and substantial improvement in its functions. But research continues to show the great potential earth has to respond to the enormous housing needs of millions of people around the world. Research institutions, working alongside builders, entrepreneurs, and industries, have successfully improved ways of making earth-building technology attractive, thus making it competitive to other building technologies (Rigassi & CRATerre, 1985)

In order for the use of earth to be the most cost effective way to help improve the housing situation, users must be aware of its suitability and requirements. To do so, a number of practices and skills have to be considered and put in place. Earth building construction has been in practice long before now and is still in practice in Liberia. But until the late 1960s, when the use of adobe blocks (locally called dirt blocks) became more popular in some provincial cities around the country, and now in surrounding areas of the nation's capital, the use of earth as a building material was exclusively practiced by rural dwellers and the poor. While it is true that the use of the material is progressively becoming more popular, one concern still remains: most people are doing so with little or no knowledge about the technical and scientific requirements of the material to justify its optimum benefits. Given these concerns, this paper presents in general information about earth as a building material capable of meeting technical requirements for home construction. In particular it addresses 3 of 12 common techniques believed to have the potential to meet Liberia's needs. They are adobe blocks, compressed earth, and rammed earth construction techniques.

It is preferred to use indigenous soils for building purposes whenever possible. Importing earth samples from one country to another is not an ordinary venture. The paper therefore investigates the suitability of native Liberia soils (Latosol soils) for possible use as building materials in Liberia under recognized principles of earth-building by using a local Johnson City, Tennessee, earth sample to simulate Liberia soils.

The paper also comments on the structural suitability of Liberian soils, cost-benefits associated with adding chemical stabilizer to the soil, and stabilizers that could be used to improve the performance of the native soils. Finally, the paper concludes with recommendations for future study and those befitting the practice and promotion of earth-building in Liberia.

CHAPTER 2

LITERATURE REVIEW

Overview of Earth Building Construction

Earth buildings are durable provided they are protected from excessive moisture and consequently can last for several years. For example, Egypt plays host to the world's oldest earth building near Luxor. It was built around 1300BC (Maini, *2005).* From the time man began to build homes thousands of years ago, earth has been the most widely used construction material. Nearly every inhabited continent on the face of the earth has a heritage of unbaked earth structures. Even in these modern times, more than a third of the world's population lives in homes built with earth. The use and improvement of different techniques of earth-building construction have evolved over the years. Twelve main techniques of using earth as construction material are known, but only adobe block, compressed earth, and rammed earth techniques are the main subjects of this paper.

Earth as Building Material around the World

While most people might think the use of earth for building purposes is only good for developing countries, developed countries (considering the economic and energy crisis) are committing millions of dollars in research works to extensively improve on the quality of the material (Guillaud & Houben, 2008). The practice of Earth Building Techniques has never been more crucial than now when costs of conventional construction materials and transportation are on the increase, and global warming, partly attributed to de-forestation, is increasingly becoming a concern. In the case of Liberia, the practice is particularly important to combat all of the aforementioned as well as to minimize erosion threats now faced by cities along the seacoast due to continuous sand mining operations for sand-cement types of construction.

.Advantages and Disadvantages of Earth-Building

Advantages

Building with earth comes with several advantages, among which are the following:

1. Less energy to produce - unlike its rival materials (cement, baked blocks, processed wood) earth block production does not require as much electrical or mechanical energy.

2. Flexibility of production - the material can be processed on site, be it in a rural or urban area.

3. Availability of production equipment - the availability of press machines on the current market makes the adaption of the technology more appealing.

4. Common dimensions - because of their common dimensions, earth blocks are flexible in the use of building construction.

5. Availability of raw material - for the most part, needed volume of earth is usually available on the site of the construction and does not require transportation.

6. Availability of help - with little supervision, construction with earth can accommodate help from unskilled workers, friends, or family members.

7. Environmentally friendly - the material is not toxic, and it is the only construction material that can be used many times (Rigassi & CRATerre, 1985).

Disadvantages

Like all other building materials, building with earth is not without problems, but most of its disadvantages can be remedied by just following the principles of use. Chiefly among the disadvantages are the material's vulnerability to water and the intensiveness of labor.

What Is Earth Made Of?

Earth is composed of various soil types and may be formed in layers of topsoil, subsoil, decomposed rock, and rock. Figure 1 illustrates a typical soil profile and the zone (Horizon) in which each type may be found.

Top soil -Zone (1)	Zone (1) - this zone is where top soil is found. Soil here contains organic materials and usually dark in color. Soil not recommended for building.
Sub Soil – Zone (2)	Zone (2) - Soil from this zone is likely to be beige in color and will feel sticky if it contains clay
--- Sub soil – Zone (3)	Zone (3) – this zone contains soil that is likely sandy and therefore does not retain water.
Bed Rock Zone	Continuous masses of hard rock that cannot be excavated by hand are present in this zone.

Figure 1. Typical Soil Profile

The composition of earth varies from one region to another and with depth from which the sample is taken. Subsoil, the layer immediately beneath the top soil, is the soil most commonly used for earth construction. Subsoil is made up of varying proportions of four types of material: clay, silt, sand, and gravel. Each of these behaves in unique ways: for example, when exposed to variations in moisture, gravel and sand mixtures will remain stable while clay and silt mixtures will not (Guillaud & Houben, 2008).

Definition of Soil Types

Clay - clays are the finest size particles of soils (less than 0.002mm); they have uniquely different characteristics than those of the other particle types. They consist mainly of microscopic mineral and particles. The film of absorbed water links micro-particles of the soil together, which gives clay its cohesion and strength.

Silt - silt is made up of particles size ranging between 0.002 and 0.06mm; they have little cohesion when dry. As their resistance to movement is generally lower than that of sands, they display cohesion when wet; when exposed to different levels of humidity they swell and shrink, resulting in volume changes.

Sand - Sand is made up of mineral particles, the size of which ranges between approximately 0.06 and 2mm. Though a stable constituent of soil, sands lack cohesion when dry.

Gravel - Gravel is made up of pieces of rock of varying hardness, the size of which ranges between approximately 2 and 20mm. They form a stable constituent of the soil. The mechanical properties undergo no detectable change in the presence of water *(Michigan Department of Transportation*, 2009*).*

Soil Properties

Gravel and sand, and sometimes silt, are characterized by their stability in the presence of water. When dry, they have little or no cohesion and therefore they cannot be used on their own as the principle material for a building. To counteract this deficiency in the material, earth material to be used for building purposes must contain the right amount of clay in order to achieve the desired bonding strength. On the other hand, because clay swells and shrinks with changes of moisture content, the presence of excessive amounts of clay content is likely to be unmanageable. Clay is a very important element in earth construction but also a problematic ingredient. In order for the earth sample to be considered fit for building construction purposes, it must contain approximately 10% to 20% clay (Rigassi & CRATerre, 1985). Figure 2 demonstrates how the soil materials may be proportioned to achieve maximum effect for building purposes.

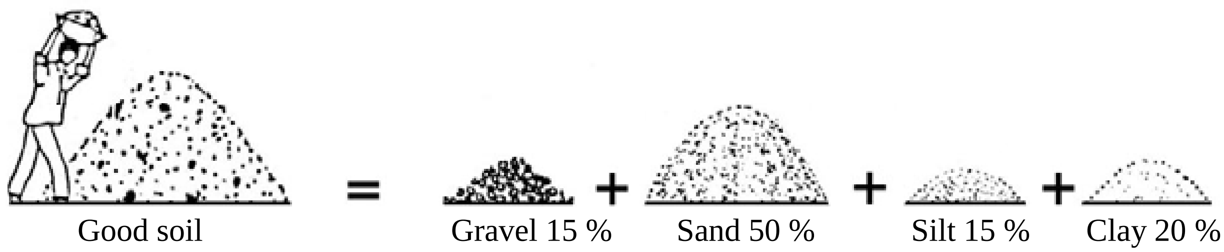

Figure 2. Good Soil Equation.
Source: Maini (2005). Earth Architecture for Sustainable Habitat and Compressed Stabilised Earth Block Technology.

The properties of soil change from one soil type to another depending on the nature of the particle fractions making up the soil and the complex way in which the particles are mixed together. Usually it is the dominant particle fraction of a soil that characterizes its fundamental properties and dictates its behavior, and even its name or classification. One can distinguish soil on the basis of its chemical and physical properties. Physical properties include color, structural stability, adhesion, apparent dry density, moisture content, porosity, absorption capacity, permeability shrinkage, dry strength, and many more. Understanding the chemical and physical properties enables one to define the quality and performance of the soil for building purposes.

However, it may not be possible to have full knowledge about the chemical and physical properties of the soil before deciding to use it for building purposes. What is important though, is to have a very good idea of three fundamental properties, which are:

1. The texture or particle size distribution of the soil – this determines the percentage of clay, silt, sand, and gravel present. It is determined by particle size analysis for the coarse fraction (gravel sand and silt) and by sedimentation analysis for the fine fraction (clay).

2. The plasticity of the soil, or the ease with which it can be shaped - this defines the extent to which the soil can be distorted without any significant elastic reaction, typically cracking or crumbling. The plasticity of a soil, as well as the limits between different states of consistency, is defined by measuring the “Atterberg Limits” (discussed later in the text).

3. The compressibility of the soil - this is the extent to which voids and therefore porosity of the soil can be reduced to the minimum.

The Effect of Water on Soil

Soil behavior and properties change in the presence of water. The effect water has is to introduce mechanical forces due to the phenomena of capillarity. These forces and the absorption capacity are greater for soils with finer particle size. For clay, the most active soil type, electrostatic forces are also present; they cause it to be more cohesive and highly plastic. Mixing the soil with water makes it possible for one to determine its absorption capacity, cohesion, and plasticity. In order to test this behavior, sample blocks are molded and observed while in the drying process. The results point out loss of cohesion for samples made from gravelly, sandy, and silty soils, while those made from a clay-type soil will keep their shapes, though showing cracks developed as a result of shrinkage.

Hydrous States of Soil

The reaction of soil in the presence of water varies with the amount of water absorbed. There are four common hydrous states: dry, moist, plastic, and liquid. Each state has a corresponding application which is dependent on the nature of the soil and the building system used. Application will depend on whether or not the region has low rainfall and also on the tradition and skills of the people involved with production (Rigassi & CRATerre, 1985).

How to Find the Best Soil

Exploration

Materials for building are not found at the surface, neither are they found at greater depths. Materials found at the surface typically are organic materials, while those found at greater depths are solid rock. The depth at which soil for building can be found varies extensively between a few meters and several meters (Rigassi & CRATerre, 1985).

Where to Look

Sources such as maps from geological, topographical, agronomical, or road works may provide information on the soil where the project is to be carried out. Another potential source is the people living in the area of the proposed project site. Local residents may be able to supply conclusive information, particularly if earth is being used for local buildings, suggesting usable deposits. Earth for building often lies below a layer of organic soil, thus it is important not to embark upon sampling that is not controlled and to remember that organic soil, which is not useful for building, may be useful to local farmers (Guillaud & Houben, 2008).

Collecting samples

Sample material may be taken from bore holes, open trenches, or the combination of both. Samples should be taken from homogenous layers. Depending on the scale of the project, these can be chosen "by eye" or by using statistical sampling system. The sample size and weight will depend on the number of tests to be carried out. In general 1 to 2 kg is enough for field testing. To test for compressibility (using proctor test), 6 to 10 kg is needed, and to make a sample block (measuring 29.5 x 14 x 9cm) approximately 10kg is needed. The sample taken must be representative. Different soils should not be mixed together to compensate for shortage. Instead, a greater number of samples should be taken. Samples should be labeled for easy identification. In addition, any data such as who took the sample and from where was the sample taken should be noted (Guillaud & Houben, 2008).

Soil Identification Techniques

Laboratory Techniques

Following the collection of the soil sample, it may be put through four common laboratory tests to determine its appropriateness for the project.

Grain size distribution. This test is carried out by sieve analysis in which the soil is filtered through a series of standard mesh sieves placed one above the other in the order of decreasing opening size, and the proportion of material left in each sieve determined.

Sedimentation analysis. The grain size distribution analysis obtained by passing the sample through sieves is not always sufficient. It works for most road works applications but is insufficient for the purpose of building with earth, which requires analysis of particles having diameters less than 0.08mm. In this case, sedimentation analysis is the appropriate test because it exploits the different speeds at which particles of soil suspended in water will settle; the coarsest will settle first and the finest last. Variations in density are measured at regular intervals and at a given height (density diminishes as the liquid clears).The speed at which the particles settle enables one to calculate the proportions of the various sizes of particles.

Proctor test. In order for soil compaction to be efficient, the compaction process must be carried out on a moist material, the moisture content of which is optimum. This is crucial because if the moisture content is higher than necessary, the soil may swell and the pressure of the compacting machine will be disrupted by the water trapped between the particles. On the other hand, if the moisture content is too low, the particles will be insufficiently lubricated and it will not be possible to compact the soil to its minimum volume. This dilemma calls for the determination of what is known as the optimum moisture content (OMC), which is the moisture content above or below which the soil will decrease in strength.

Atterberg Limits. Soil has various states of consistency including liquid, plastic, or solid. A Swedish researcher named Atterberg defined these various hydrous states and the boundaries separating them as limits and indices:

A. Liquid Limits (LL); this is the amount of water expressed as a percentage corresponding to the point at which the material passes from a plastic state to liquid state.

B. Plastic Limits (PL); this is the point at which the texture passes from being plastic to solid. At the liquid limits the soil begins to display some resistance to shearing, and at the plastic limits it ceases to be plastic and becomes crumbly.

The two quantities, plastic limits and liquid limits, define one key indicator, which is the plasticity index (PI). PI is the difference between the liquid limit (LL) and the plastic limit (PL), and it determines the extent of the plastic behavior of the properties of the soil. Mathematically, PI = LL – PL. Together, the liquid limits and plastic limits also define the sensitivity of the soil with changes in moisture content. Soil can also be classified depending on the measure of its plasticity index and the liquid limits as indicated below; this is further explained by Figure 15, Appendix C.

1. Soil with PI from 1 to 10 and LL from 0 to 30 is considered to be a sandy soil;
2. Soil with PI from 5 to 25 and LL from 20 to 50 is considered to be a silty soil;
3. Soil with PI greater than 20 and LL greater than 40 is considered to be a clayey soil.

Field Techniques

Depending on the needs of the project, and the degree to which data collected must be accurate, simple field tests can be carried out instead of the usual laboratory tests, which are more costly. There are four common field tests, Touch/Smell/Washing, Cigar, Biscuit, and Jar tests. Only the jar test is discussed further as it is inexpensive, effective, and can produce quantifiable results.

Jar test. Take a transparent cylindrical jar or bottle of at least 1/2 liter capacity and fill it at the 1/4 mark with soils and at the 3/4 mark with water, seal the top using your hand or lid, and shake well. Leave the jar to stand for at least 30 minutes and observe the sedimentation layers.

After resting for about 30 minutes or more, particles in the solution of soil and water will begin to settle in layers. Coarse material (gravel) will be deposited on the bottom, followed by sand, then silt, with clay at the top. The depth of each layer approximately gives an indication of the proportions of each type of material (Guillaud & Houben, 2008).

Strength Requirement of the Soil

In order for the soil to be considered adequate, it must possess certain minimum mechanical properties. One critical mechanical property is compressive strength. Therefore prior to considering the soil for building construction purposes, samples must be tested to determine compressive strength. Generally for single-story residential buildings, the required compressive strength lies between 10 and 20 N/cm^2 (14.5 and 29lbs/in^2) (Guillaud & Houben, 2008). Guillaud and Houben also suggest the use of an overall strength coefficient of 20 to 30 to account for safety conditions such as variation in production quality, accidental excess loading, nature of material, buckling of wall, ratio of wet strength to dry strength, etc. Using a strength coefficient of 25 would result in required compressive strengths of 250 and 500N/cm^2 (363 and 726lbs/in).

Soil Stabilization and Stabilizers

Stabilization

When one speaks of stabilizing a soil in earth construction, what comes to the minds of lay people is to add Portland cement or some other additives to the soil. But adding cement or any additives to the soil is not the only means of stabilization. Stabilizing soil means to improve its properties in the wake of unavoidable circumstances. Therefore any actions taken to improve the properties of the soil are considered stabilization.

Methods of stabilization. There are three basic known ways or procedures by which soil can be stabilized:

1. Mechanical stabilization – by this procedure, the soil is compacted to affect changes in its density, mechanical strength, compressibility, permeability, and porosity.
2. Physical stabilization – by this procedure, the properties of the soil can be modified by acting on its texture, for example controlled mixing of different grain fractions.
3. Chemical stabilization – by this procedure, other materials or chemicals are added to the soil, thus modifying its properties either by a chemical reaction between the grains and the materials or by creating a matrix which binds or coats the grains.

Among the three the use of chemical stabilization, the most costly, is a matter of choice, depending on the requirement of the project and the owner's preference. If the dangers of exposure to water are contained, the use of chemical stabilization will not be justified. What is important is to select the right material for the project (Rigassi & CRATerre, 1985).

Deciding on stabilization. Except for granular soil, the use of chemical stabilizer, for example cement, should be avoided in the interest of cost saving. This point is worth emphasizing because adding cement to a material having more clay content requires more than the usual doses of 4% to 8% (Adam & Agib, 2001). Table 1 can be helpful in deciding.

Table 1

Decision Guide to or Not to Stabilize

Question	Yes	No	Action
Is the structure higher than two stories?	✓		Do stabilize
		✓	Do not stabilize
Has the design taken into account fundamental principles of building with earth or location constraints?	✓		Do not stabilize
		✓	Do stabilize
Is the structure going to be exposed to excessive moisture?	✓		Do stabilize
		✓	Do not stabilize
Has the soil been tested and found to be suitable for the given project?	✓		Do not stabilize
		✓	Do stabilize
Has the structure been designed following the principles of earth building technology?	✓		Do not stabilize
		✓	Do stabilize
Does the owner insist on using stabilizer even though it has been clearly stated that the use is not structurally necessary?	✓		Do stabilize
		✓	Do not stabilize

Common Stabilizers

Some known stabilizers are:

1. Sand and gravels - these are added when the soil is not usable in its natural state, sometimes because it contains more clay than required.

2. Natural and synthetic fibers - these are commonly used traditionally to reinforce the soil, especially in the production of adobes blocks. The practice is incompatible with the production of compressed earth blocks because the mix becomes too elastic in the presence of fibers.

3. Bitumen - this has a water proofing effect but needs to be mixed in an even manner, which demands a process requiring a high volume of water, a condition most suited for adobes.

4. Cement and Lime - cement has a cementation effect and lime has a bonding effect. Cement is the most popularly used stabilizer in the production of compressed earth blocks; it is discussed in more detail next.

Cement in Earth-Blocks

Cement is the most commonly used chemical stabilizer in the production of compressed earth-blocks. Adding cement before compaction improves the characteristics of the soil, particularly its resistance to water. Cement mainly affects sand and gravel, as in concrete and sand-cement mortar. Care must be taken in its application; it may be harmful if used in soils having clay content higher than 20% (Rigassi & CRATerre, 1985).

Calculating the Amount of Stabilizer and Earth Mix

Calculations involving stabilization are always based on the mass (weight) of the dry materials. The amount of the stabilizer used is in proportion to the mass (weight) of the earth material, including any gravel or sand that may have been added. Weighing the material in the field is not difficult but is time consuming. It is recommended therefore to convert the mass of the material to volume. In order to do so, two quantities (mass and density) of the sample must be known. Mass (weight) can be obtained by weighing 1 liter of the material (earth) using a scale accurate to + or – 10g, in a loose and dry state. If such a sensitive scale is not available, a larger quantity (between 5 to 10 liters) should be weighed in similar state to reduce error. The density of the materials can be calculated knowing the volume capacity of the container used to measure the materials prior to weighing it. Once the density of the materials is known, mass (weight) of the materials can be converted to volume. Table 2 in conjunction with the following equations, Rigassi & CRATerre, 1985, can be helpful in determining these quantities.

Table 2

Definition of symbols

Symbol	Definition	Symbol	Definition
ρ_C	Density of stabilizer (kg/ m^3)	ρ_S	Density of sand (kg/ m^3)
V_E	Volume of the material (earth) m^3	C	Degree of stabilization (%)
Vs	Volume of sand (m^3)	Mc	Mass of stabilizer (kg)
E	Percentage of earth material (%)	ρ_E	Density of earth(kg/ m^3)
S	Percentage of sand (%)	Vc	Volume of stabilizer (m^3)
M1	Mass of empty can (g)	W%	Moisture content
M2	Mass of can + moist soil (g)	PI	Plasticity Index
M3	Mass of can + dry soil	PL	Plastic Limit
LL	Liquid Limit	N	Number of blows
Note: The material (earth) is the combination of gravels ,sands, silts, clays and humus			

$$\text{Density of the material } (\rho_E) = \frac{\text{mass (weight) obtained by weighing the sample (kg)}}{\text{Volume of material } (m^3)\text{, from container of known capacity}} \qquad (1)$$

$$\text{Volume of the material } (V_E) = \frac{\text{mass of the material (kg)}}{\text{Density of the material } (\rho_E)\ kg/m^3} \qquad (2)$$

How much stabilizer? To determine how much stabilizer is needed, one must have available a container of known capacity (e.g. wheel barrow = 60 liters, buckets between 10 to 15 liters capacities) to allow for precise calculations. The amounts required for the desired mix will be a multiple of whatever measuring container used. The degree of stabilization, in this case the required percentage of cement (C) or Bentonite (B), (e.g. 4, 8, 10, 20, etc.), must be determined in advance. Having determined the required volume of earth (V_E), its density (ρ_E), and the degree of stabilization, the mass (weight) of the required stabilizer, for example cement (Mc), can be determined from the equation,

$$Mc = \rho_E \text{ x } V_E \text{ x } C/100 \qquad (3)$$

Or if the mass (weight) of the desired quantity of cement (Mc) and the degree of stabilization (C) are predetermined, compute the required volume of earth material (V_E) from the equation,

$$V_E = Mc \text{ X } 100/ \rho_E \text{ x } C \qquad (4)$$

The result from Equation 4 should be rounded to the nearest multiples capacity of the measuring container, and then the degree of stabilization recalculated from the equation,

$$C = Mc \text{ X } 100/ V_E \text{ x } \rho_E \qquad (5)$$

Calculating the quantity of earth and stabilizer in a mix. Obtain the mass (weight) of the stabilizer, for example cement, from the volume of earth (V_E) with known density (ρ_E) and the degree of stabilization(C) from the equation,

$$M_C = [(\rho_E \times V_E) \times C]/100 \quad (6)$$

Obtain the volume of Earth and the degree of stabilization using the following equations, where E & S are the total volume of earth material and percentage of sand or gravel present respectively. Also ρ_S & V_S, ρ^g & V^g or are the density and volume of sand or gravel, respectively.

$$V_E = M_C / \rho_E \times C \quad (7)$$

$$V_S = M_C \times S / \rho_S \times C \quad (8)$$

The result from equation 8 should be rounded to the nearest whole volume of site measuring container, and then the degree of stabilization recalculated using the equation,

$$C = M_C \times 100 / (\rho_E \times V_E) \quad (9)$$

The percentages of gravel (G) and sand (S) present in the earth material can be precisely calculated respectively from the equations:

$$G = [\rho^g \times V^g / (\rho_E \times V_E)] \times 100 \quad (10)$$

$$S = [\rho_S \times V_S / (\rho_E \times V_E)] \times 100 \quad (11)$$

The density of cement (ρc) can be calculated from the equation,

ρc = weight of cement (kg)/volume of cement (m^3) (12)

Sample Problem - the volume and density of a sample of earth are respectively $5m^3$ and $2kg/m^3$. If 4% is the predetermined degree of stabilization, calculate the weight of cement required and the multiples of container measure, given the container has a capacity of $0.061m^3$.

Solution - from equation 3,

$Mc = \rho_E \times V_E \times C/100 = 2kg/m^3 \times 5m^3 \times 4/100 = 40\ kg \times m^3/m^3 \times 100 = 0.40$ kg.

With the mass (weight) of cement determined to be 0.40 kg, recalculate the volume of earth using equation 4:

$V_E = Mc \times 100/ \rho_E \times C = 0.40\ kg \times 100/ 2kg/m^3 \times 4 = 5\ m^3$.

Using a measuring container having the capacity of 0.061 m^3 (for example, a container with dimension, 0.45m x 0.45m x 0.3m), and a required $5m^3$ material, determine the number of multiples from the equation,

Number of multiples = Volume of earth required/volume capacity of container

= $5m^3/0.061m^3$

= 81.967 or 82 measures of container.

That is, use 82 measures of dry earth (using a container with capacity $0.061m^3$) and 0.40kg of cement for this mix.

Mixing the cement and the soil - mixing the cement with the soil evenly is very crucial. Lumps of clay or other materials must first be removed. After screening, care must be taken to prevent lumps from reforming, meaning the soil must be kept dry. The proportion of cement in the mix should be kept at a level not exceeding 4% to 8%, and must be mixed vigorously to blend the cement and the soil prior to adding water for the final mixing process (Rigassi & CRATerre, 1985).

Selective Earth Building Construction Techniques

For a long time earth has been used as a construction material to build homes and other structures. Over time different techniques have evolved. Twelve different techniques are recognized today in the earth building construction industry. Among them only three, adobe, compressed earth, and rammed earth seem to be applicable to the housing needs of Liberia. They are discussed in the following order:

Adobe Blocks Technique

Adobe blocks in review - adobes are earth blocks produced using highly saturated soil. The traditional way of production is to use wooden or metal molds to form the material, but nowadays the use of machines is prevalent.

Using adobes for building construction is an ancient technique dating to Jericho (8300 BC). Buildings built with adobes are among the world's oldest structures. For example, some built more than 900 years ago are still in use in North America. The technique is still in widespread use around the globe and is being practiced not only in developing countries, but in developed countries as well. The use of the technique is visible in southwestern United States.

Adobe blocks are simple to produce and easy to apply. Cracking due to shrinkage is not a threat to buildings built using adobe blocks because shrinkage takes place while the blocks are cured. Other unique qualities of adobes are the variety of soils from which they can be produced and their ability to cope with more clay content than their counter parts. Often a mud render, sometimes containing a dust retardant (traditionally a mixture of clay and fine sand) is applied as a surface coating, the effect of which is to cover uneven walls and to protect walls from moisture intrusion, (Adam & Agib, 2001).

Production of adobe blocks. Adobe blocks are produced using simple wooden or metal molds with sizes dependent on the project requirement. The most popular mold sizes are 25.4cm x 10.16 x 35.56cm (10" x 4" x 14"). Unlike other earth blocks, the production of adobe blocks requires only simple construction tools and equipment; wheelbarrow, shovel, hopper, potable mixer, pails, and 0.60cm (1/4") diameter wire mesh. The wire mesh is used to screen the material, making sure that particles size > 0.635cm diameter is not included in the mix.

The soil may or may not be mixed with various additives depending upon project requirements. Additives and stabilizing materials such as cement, Bentonite, or lime may be added to improve the compressive strength of the blocks. Straw may be used to improve the tensile strength, while asphalt emulsion may be added to the dry mix to improve the water proofing quality, the elasticity, and toughness of the blocks.

Production process. Following the mixing of the required amount of material, water (quantity predetermined from trial batches) is added to the dry soil and mixed to a consistency equal to that of the accepted trial batch. Then the mixture is poured into the open mold and compressed.

The mold(s) can be withdrawn straightaway or the next day depending on the size of operations. Following are steps common to manual block production:

1. Select and clear a large area of land (production yard) for mixing, molding, and curing the blocks.
2. Extract the needed volume of soil material from a predetermined site and process, if necessary, by screening using a 0.635cm (1/4") diameter wire mesh.

3. Mix a predetermined volume of soil material with water, the volume of which should be equal to the optimum moisture content of the earth material being used.

4. Set the mold (s) up on a prepared level ground area over a plain metal sheet or building paper (if available) and dump the mixed product, a quantity just enough to produce one block, into the mold, using a wheelbarrow, hopper, or shovel.

5. Using a flat wooden tamper, work the material firmly into all corners of the mold, then scrape the excess material off, extract the block, and move to the curing site.

6. Repeat the cycle until the desired quantity of blocks has been produced.

Curing the blocks. To ensure adequate strength, the blocks must be allowed to cure for about 14 days. During the first 7 days the blocks are wet cured (wetting the blocks each day for 7 days). During curing, the blocks must be turned regularly to allow for uniform drying, (Rigassi & CRATerre, 1985). Figure 3 shows a production yard and the curing process.

Figure 3. Adobe Yard – the curing process
Source: Earth Building Association of New Zealand (1999)

Compressed earth blocks technique

Compressed Earth Blocks in Review. Generally, compressed earth blocks are an improved version of adobe blocks. Compressed blocks have improved in quality over time with the invention of production equipment. The first compressed blocks were produced using wooden tamps probably before the 18th century. Then came the beginning of the 20th century when the first mechanical presses were designed, followed by the 1950s when the CINVA-RAM press machine was invented by engineer Raul Ramirez at the CINVA center in Bogota, Columbia. The 1970s and 1980s saw a new generation of manual, mechanical, and motor-driven presses, making pressed blocks more attractive. Compressed earth blocks may be improved further by mixing the soil with an additive, the most common being cement. Blocks produced in this manner are called compressed stabilized earth blocks (Rigassi & CRATerre, 1985). The first two pictures from the left in Figure 4 are pictures of examples of press machines and the third one is form work for rammed earth wall.

Figure 4. Examples of press blocks and rammed earth form work
Source: Maini (2005)

Production. Having identified the soil and tested its suitability, the same steps for the production of adobe blocks may be followed except that the moisture content required for the production of pressed blocks is generally less.

Curing the blocks. As the blocks are removed from the mold, they are inspected for defects. Satisfactory blocks are carefully stacked on a clean, flat, level surface in the shade to cure. This may be the floor of a pre-existing structure or under the roof of the house being constructed (held in place by temporary or permanent poles). The same curing principles used for adobe blocks are applicable for pressed blocks except that pressed blocks are stacked. Figure 5 is a picture showing the curing process of compressed earth blocks.

Figure 5. Compressed specimen Blocks going through the Curing process

Rammed Earth Technique

Rammed earth in review. The exact age of Rammed Earth construction is not known, but Hannibal's rammed earth watch tower confirms the practice of the technique hundreds of years before Christ (Tibbets, 2001). Another mystery of rammed earth technique is its origin. Nearly every old culture has evidence of its existence: from cites in Africa to the historic wall of China. Its inception is believed to be linked to older builders' desire for easier ways of construction. Unlike its counterpart, adobe blocks construction, rammed walls are built in-situ using form work, a characteristic that gives it a time advantage over other techniques of earth building constructions. The soil is moved only a few times compared to the number of times soil for adobe or compressed earth blocks has to be moved. The fact that the walls are built in place, waiting time for curing before putting the products in to use is reduced, an advantage to rammed earth users.

In the 1800s in the United States, rammed earth was popularized by a book, Rural Economy written by S.W. Johnson. For example, it was used to construct Borough House Plantation and Church of the Holy Cross in South Carolina, which are two National Landmarks of the United States. From the 1920s through the 1940s, millions of dollars were spent by the US Government and several western universities researching rammed earth construction. In 1945 Clemson Agriculture College of South Carolina published its results on rammed earth research in a pamphlet called "Rammed Earth Construction." Today, Rammed Earth technique is part of the growing earth home construction industry in the southwestern part of the United States (Tibbets, 2001).

Method of construction. With a suitable foundation in place and an adequate formwork made of wood or metal on hand, the following steps are common for rammed earth technique:

1. Formwork is setup to create the desired shape of the section of wall.

2. The soil is dry mixed to guarantee a uniform distribution of the soil particles, then stabilizer added, if desired, and remixed. This is followed by adding water to the mix.

3. The damp mixture is poured into the form to a depth ranging from 100mm to 250mm (4 to 10 inches) and tampered to about half of its original depth

4. Repeat step 3 until walls of the building are built.

Figure 6 shows a picture of rammed wall under construction.

Figure 6. Rammed wall under construction

Source: Earth Building Association of New Zealand INC (1999)

Curing the Walls. Curing time for rammed earth wall varies depending on wall thickness and degree of saturation but could take as long as 3 months. The durability of rammed earth structure is assured as long as it is protected against excessive moisture. Rammed earth walls can attain a compressive strength of 19.62 to 58.86 N/cm² (30 to 90 psi) immediately following erection; ultimate being 314 to 549 N/cm² (450-800 psi), (Christensen, 2009*)*.

Liberia's Geography & Soil Classification

Overview of Liberia's Geography

Liberia is located on the west coast of Africa, and is bounded by Sierra Leone on the west; Guinea Republic on the north; Côte d'Ivoire (Ivory Coast) on the east; and the Atlantic Ocean on the South. The Atlantic coastline to the west is 560km (348 miles) long, of which more than half is sandy beach. The area of Liberia is about 99,055km² (38,250 square miles). Lying parallel to the shore are three distinct belts. The low coastal belt is well watered by shallow lagoons, tidal creeks and mangrove swamps behind which rises a gently undulating plateau, 500 to 800m (1,640 to 2,625ft) high, partly covered with dense forests. Inland and to the north is the mountain region that includes Mount Nimba at 1,752m (5,748ft) and Waulo Mountain at 1,400m (4,593ft), (Reed, United States Department of Agriculture and United States Department of State, 1951). The population of Liberia (according to the 2008 National population and housing census) is 3,489,000.

Weather and Climate in Liberia

Liberia has a tropical climate with average temperatures ranging from 21°C to 37°C (70 ° F to 100 ° F). There are relatively small variations between day and night and between seasons. There are two seasons – the wet season is from May to October and the dry season is from November to April. It rarely rains during the dry season, though there are dry periods during the rainy season, including a dry spell in July or August lasting about 2 weeks. The annual rainfall averages 4,320 mm (170 inches) inland. The average humidity on the coastal belt is 78% during the wet season, but can drop to 30% from December to March when the Harmattan winds blow from the Sahara (Reed, 1951).

Classification of Liberia Soils

Major Soil Types

From 1944 to 1948 the United States Government sponsored a soil survey of Liberia's soils that grouped the soils as Latosol, Lithosols, and Regosols. Figure 7 is the soil map.

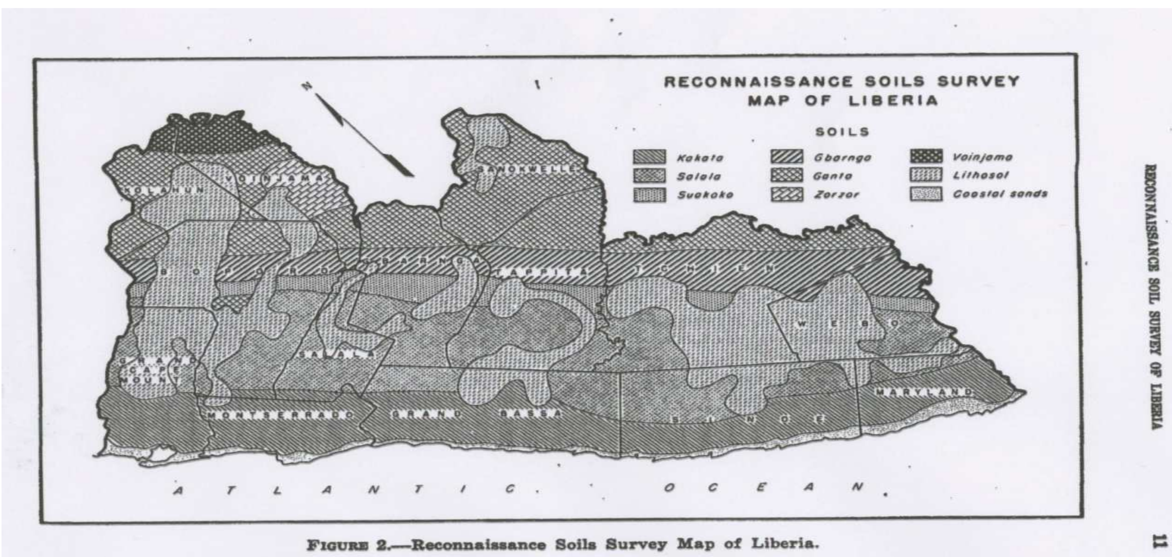

Figure 7. Soil map of Liberia

Source: Reed (1951)

Latosols

The Latosols occupy about 75% of the nation's total land area. They occur on undulating, gently rolling, or steeply rolling land that varies in elevation from sea level to about 550 meters (1,800 feet). Some of the soils are under original tropical high forest vegetation, while those that are used for farming are for the most part under a secondary growth of low trees.

The parent materials of these soils are crystalline metamorphic and igneous rocks. Latosols vary in thickness over bedrock from a few meters to considerable depth. Latosols can be further classified as Kakata, Gbarnga, Ganta, and Zorzor soils. Kakata, Gbarnga, Ganta, and Zorzor, refer to major towns in which the Latosols are found. Each subclass is briefly described as follow.

Kakata soils. The Kakata soils are brownish red in color and consist of sandy loams and clay loam, a quality suitable for building construction. They occur on gently rolling to rolling topographic in a rainfall belt that ranges from 3 to 4 meters (120 to 170 inches) precipitation. The topsoil on the ridges contains a considerable amount of dark-brown and black gravel (lateritic) and is very compact, especially when the moisture content is low. From surface to bottom, the soil's layers range from a very thin layer of peat to sandy clay and clay 46 to 91 cm (18" to 36") thick.

Gbarnga soils. The Gbarnga soils are pinkish red in color and consist of sandy loams and sandy clay loams. The annual rainfall in the areas in which they occur, ranges from 2 to 2.5m (80 to100"). From the surface to the bottom, the soil's layers range from a very thin layer of peat to sandy clay 18 to 130cm (7 to 50") thick.

Ganta soils. The Ganta soils are reddish-yellow in color and consist of sandy clay loams and clay loams. From the surface to the bottom, the soil's layers range from a very thin layer of peat to sandy clay 23 to 200cm (9 to 80") thick.

Zorzor soils. The Zorzor soils are red in color and consist of deep red clays developed on syenitic rocks. These soils are characterized by their red color. From the surface to the bottom, the soil's layers range from a thin layer of peat to sandy clay 20 to 178cm (8 to 70") thick.

Lithosols

Generally the Lithosols occupy hilly and rugged land; they represent more than 16% of the total land area of Liberia. Lithosols are shallow soils, varying in depth from several centimeters to a few meters. Most of the deeper soils are alluvia formation. Trees and shrubs make up the vegetation of the soil. The clay in some of the soil is plastic and in some it is non-plastic.

Regosols

Sands dominate the Regosols soil group of Liberia. They occur in the narrow coastal belt and in several small tracts farther inland. Sands along the coast are ocean deposits; those inland are developed from coarse sandstones. Vegetation consists of a sparse stand of savannah-type growth and palms. The sands are inherently infertile and are not good for common crops production unless fertilized.

Particle Size Distribution of Liberia's Soils

Particle size distribution in soils is of great importance in the earth construction business; compressibility of a soil highly depends on how well its particles are distributed. Liberia's soils particles distribution ranges are summarized in table 3.

Table 3

Range of Particle Size Distribution of Liberia Soils

Gravels	Sands	Silts	Clays	Humus
0 % to 76%;	31% to 98%;	1% to 39%;	1% to 46%.	0% to 4%

CHAPTER 3

METHOD OF RESEARCH

Introduction

The two main objectives of this research are to explore earth building technology and determine what would need to be done to Liberia's soils so that the principles of earth-building can apply for building purposes. To address the issues, a literature review of Earth-Building Technology was conducted and information on the geography and soil types of Liberia was explored. In addition to reviewing existing documentations on Liberia's soils, soil sample test analysis results were obtained from the Agriculture Department of the University of Liberia. The data gathered through this process were used to determine the feasibility of using a local Johnson City, Tennessee, earth sample to simulate Liberian soils. Upon determining that a local Johnson City, Tennessee, earth sample could be used to simulate Liberian soils, specimen blocks were produced using the local earth sample. The specimen blocks were tested to determine compressive strengths and a cost-benefit analysis performed based on stabilization content and corresponding strength.

Limitations

To further define the extent of the second objective above, limitations were placed on the research. The limitations were as follow:

1. That raw materials used were those of Liberia soils characteristics.
2. That only one-story residential buildings were considered. Examples regarding cost analysis and strength are described later, using an example house.
3. That the United States building codes used in Liberia were accommodated.

4. That exterior walls were overlaid with 1.3 to 2.53cm (1/2” to 1”) thick sand –cement motor to protect the walls from moisture intrusion and loss.

5. That the chemical stabilizers used in the blocks were restricted to Bentonite and Portland cement only.

6 That the principles and requirements for earth building construction were strictly followed

7. That Table 1 was used to guide the decision to use or not to use chemical stabilizer.

Specimen Block production Process

After it was decided that the local Johnson City, Tennessee, earth sample could be used to simulate Liberia soils for the experiment, two faculty members at East Tennessee State University (ETSU) in Johnson City, Tennessee were conferred with in designing the appropriate experiment. An experiment matrix was developed that incorporates two different chemical stabilizers; Bentonite and cement, with each stabilizer tested at two concentrations of 5% and 8%. In addition, each concentration of stabilizer was tested at six different moisture contents in order to determine the relationship between stabilizer concentration and moisture content. Five samples were produced for each combination resulting in the production of 150 specimen blocks, including the control blocks. The developed matrix is reported in Table 4.

Table 4

Specimen Blocks production matrix

Moisture content (%)	Natural soil (control)	Soil + 5% Bentonite	Soil + 8% Bentonite	Soil + 5% Cement	Soil + 8% Cement a	Total
18	5	5	5	5	5	25
20	5	5	5	5	5	25
22	5	5	5	5	5	25
24	5	5	5	5	5	25
26	5	5	5	5	5	25
30	5	5	5	5	5	25

Excerpts of Soil Data from Liberia

Because the reference document of Liberia's soils used in this paper is more than 50 years old, and importing foreign soil into the United States was not feasible, soil data were obtained from Liberia to enhance the experiment. The data collected from western Liberia (where Latosols are also found) by James Kazulu of the University of Liberia, were used as reference to identify a local (Johnson City, TN) earth sample with similar particle size distributions as those of the samples of Liberia. Table 5 contains excerpts from the soil data obtained from Liberia (Appendix D).

Table 5

Excerpts of soil data from Liberia

	Depth (inch)	pH (H2O)	pH (KCl)	Humus (%) (Estimate)	Clay (%)	Silt (%)	Sand (%)
Site 1							
1.2	7.0 - 15	5.8	4.5	3.5	24.7	19.6	52.2
1.4	25 - 40	6.2	4.6	< 0.5	42.2	19.6	37.7
Site 2							
2.1	0 -7.0	5.8	4.6	3.5	33.2	23.6	39.7
2.2	7.0 - 18			3.0			
2.3	18 - 25	5.6	4.5	2.5			
Site 3							
3.1	0 - 5	6.1	4.6	3.5	27.6	19.2	49.8
3.2	5.0 -18	5.8	4.7	3.5			
3.3	18 - 40	5.7	4.6	<0.5	35.5	16.1	47.9
Site 4							
4.1	0 -7			4.0			
4.2	7.0 - 20	5.8	5.0	4.0	22.9	15.4	57.7
4.3	20 - 30			3.0			
Average	5.83	4.62	2.88	31.0	22.07	47.5	

Local Earth Sample Collection and Classification

Collection and Processing of Local Earth Sample

In order to establish whether the local Johnson City, Tennessee, earth sample has the same particle size distributions as those of the analyzed earth sample data obtained from Liberia, over 180Kg of earth sample was collected from a road construction site in Johnson City, Tennessee, U.S.A. The sample was collected in its moist state with moisture content later determined to be 31.40%. The soil was spread flat with a thickness not exceeding 5cm , and allowed to dry for about 2 weeks in a room with daily temperature not more than 27°C (80°F). Following the drying period, the sample was processed through a 0.64cm (1/4″) diameter wire mesh to remove particles of greater diameters. The mass of the processed earth sample was determined and found to be 127kg. Following this, the sample in its dry state was transferred into a plastic container and well sealed to prevent it from possible contamination.

Classification of local Earth sample

In order to classify the earth sample as sandy, clayey, or silty, it was put through two different tests - Jar and Atterberg Limit tests. The results from these procedures are provided in the following section.

The jar test. A transparent cylindrical plastic jar about 1/2 liter capacity was used for sedimentation purpose. The jar was filled to the 1/4 mark with dry soil sample; to the 3/4 mark with water, and the lid put in place and well shaken. The jar with its content was allowed to sit for 16 hours. After this the thickness of sedimentation layers in the jar were evaluated and corresponding percentages recorded as shown in Table 6.

Table 6

Jar Test Results

Description	Organic material	Clay	Silt	Sand	Total
Thickness of settled particles	0.160cm (1/16”)	2.22cm (7/8”)	1.25cm (1/2")	3.20cm (1¼”)	6.83cm (2 11/16”)
Local soil particles present	2.34%	32.50%	18.30%	46.85%	99.99%
Liberia’s Soil particles present	3.25%	32.25%	18.9%	46.25%	100.65%

The Atterberg Limit tests. In order to confirm the jar test, the local Johnson City earth sample was also put through the standard Atterberg Limit tests to determine the Liquid and Plastic Limits. The general moisture content equation (Equation 13) was used to evaluate the data that are recorded in Tables 7 & 8 for Liquid Limits and Plastic Limits, respectively.

$$W\ \% = [(M2 – M3)/ (M3 – M1)]\ X100 \qquad (13)$$

Table 7

Liquid Limits Test Data

Test No.	1	2	3	4	5
Mass of empty can(M1)g	30.2	30.4	30.6	30.9	30.4
Can + moist soil(M2)g	42.8	47.1	42.0	45.5	40.1
Can + dry soil(M3)g	40.7	44.3	40.0	42.8	38.4
Moisture content%	20	22	23.3	24.7	25.3
# of blows (N)	40	35	25	15	10
Note: Liquid Limit (LL) is the moisture content that corresponds to N = 25 blows = 23.3%					

Table 8

Plastic Limits Test Data

Can #	1	2	3
Mass of can, M1 (g)	30.8	31.1	30.9
Mass of can + moist soil, M2 (g)	50.1	58.4	54.4
Mass of soil + dry soil, M3 (g)	47.6	54.5	51.7
Moisture content % = {[(M2 – M3)/(M3 – M1)] X 100}/3 = Plastic limit of the soil = 15.82%	14.9	17.2	15.35

From Table 7, the Liquid limit of the local Johnson City, Tennessee, earth sample was determined to be 23.3%. Liquid Limit (LL) is the moisture content expressed as a percent that corresponds to N = 25 blows. From Table 8, the Plastic Limit (PL), which is the moisture content at which the soil crumbles when rolled in threads of 3mm (1 /8") diameter was determined to be 15.82%. From these findings, the plasticity index (PI), which is the difference between the Liquid Limits and the plastic Limits, was determined to be 7.48%. Together, the tests indicated the following:

1. $1 < PI < 10$, and $0 < LL < 30$ = sand
2. $5 < PI < 25$ and $20 < LL < 50$ = silt

However, per Table 6 the percentage of sand in the sample is greater, followed by clay, hence the local earth sample can be classified as sandy-clay using the Unified soil Classification System (Rigassi & CRAGTerre, 1985).

Production and Curing of Specimen Blocks

Apparatus

The apparatus used to produce the specimen blocks are cylindrical compaction molds having an effective diameter 9.5cm (3¾") and depth of 7.6cm (3"). A 4.54kg (10lbs) freely falling compaction hammer (falling height = 46cm or 18") attached to a stand having a base plate, 9.5cm (3¾") in diameter is used to compact the soil.

Production

Once the soil is classified and determined to contain the right proportion of constituent materials acceptable for earth block production, it is necessary to determine the optimum moisture content that produces the highest load bearing capacity. To address this, a two-part procedure was carried out. The first part was to produce all of the specimen blocks required by the test matrix. The second part addressed testing the specimen blocks to determine load bearing strength.

Procedure: With the use of the standard compaction test apparatus, the following steps were followed in the production of the specimen blocks.

1. Quantity of processed earth required for producing five specimen blocks of the given size, and moisture content were weighed and transferred into a mixing dish.
2. For compressed stabilized earth blocks, the appropriate amount of stabilizer (5% and 8% of Bentonite or cement) was added to the dry soil, and mixed thoroughly prior to adding the desired moisture content.
3. The desired moisture content (predetermined and measure as a percent of the dry weigh of earth sample) the order of 18%, 20%, 22%, 24%, 26% and 30% was added to the designated Specimen batch of dry mix and mixed until a uniformly moistened and compressible material emerged.
4. A quantity of moistened material enough to produce a single specimen block was transferred into a mold and compacted using a 4.5kg (10lbs) compaction hammer freely falling 10 times from a height of 45.72cm (18”).
5. The mold with content was moved and inserted into an extractor and clamped in place.
6. With the mold firmly held in place, a saw knife was used to saw off excess material to the level of the mold, after which the block specimen was ejected.
7. The ejected block specimen was weighed to determine its mass, and then transferred to a designated area where it was allowed to cure for a total of 14 days.
8. Steps 1 – 7 were repeated for each specimen block containing stabilizer, while steps 1, 3 – 7 were repeated for each of the specimen blocks that contained no stabilizer.

The Curing Process

Following production, the blocks were subjected to two curing periods; a wet period followed by a dry curing period. For the wet period, the blocks were allowed to stand for 7 days, while spraying water on them once every day. Following the wet-curing period, the blocks were allowed to sit for 7 additional days, after which they were now ready for testing.

Testing Specimen Blocks

Following the curing periods, each block was put through a uniaxial compression test to determine the affect the amount of water present in the mix had on the strength of the blocks under the various stabilizing conditions. This assisted in determining if the simulated Liberia soil is suitable for earth building purposes.

Test procedure and result. Using a compression testing machine (capable of measuring compressive stress up to 3.45KN/cm² or 5000lb/in²), uniaxial compression test was carried out on the specimen blocks and the results analyzed.

Example House - Structural and Cost Evaluation

Based on the results obtained from the aforementioned tests, an example house was considered in determining the structural suitability of the soil and the cost implications for adding stabilizer to the mixture. All other formal construction procedures being the same for both earth block and sand-cement block constructions in Liberia, only the cost associated with producing the required number of earth blocks for the example house is considered in the evaluation process. The house, for which floor plan and front elevation sketches are shown in Appendix B, measures 6.1m x 12.2m (20ft x 40ft) and is built with a 15.24cm x 15.24cm x 25.40cm (6”x6”x10”) earth block to a height of 2.44m (8ft.). Single-story residential buildings in Liberia do not carry concrete roofs, but in order to test the strength of the wall under the worst case scenario, the roof of the example house is taken as a 10.16 cm (4”) thick reinforced concrete slab.

Generally the main reason for using earth for building purposes is to save cost. Therefore the task for this structural evaluation of the blocks is to determine whether blocks produced from the soil with no chemical stabilizer added can perform to expectations. The average compressive strength of the natural soil blocks was compared with the maximum actual compressive stress (adjusted by a strength coefficient of 25) expected from the example house.

The exercise is also intended to determine by how much the cost of producing the blocks would increase if chemical stabilizer is added to the soil. The exercise considered two approaches; first the cost to produce the total number of blocks (no stabilizer added) required to raise the walls of the building to a height of 2.4m (8ft) was determined, and second the cost for the same quantity of blocks, but with stabilizer added, was determined.

CHAPTER 4

RESULTS

Literature Review

Following a literature review of earth building technology, the researcher discovered that the technology is evolving globally. Though building with earth suffered a setback in the late middle ages, when the combination use of timber-frame and daub was invented through the advancement of carpentry, the technology has continued to excel. The technology began to experience revival in the years following the end of World War II, a period in which industrial materials were in short supply and the need to house thousands of homeless people was enormous. There are now huge industries of earth building all around the world, including countries in Africa.

Liberia's Soils and Particle Size Distributions

The research discovered the major soils of Liberia as Latosols, Lithosols, and Regosols. Latosols occupy about 75% of the total land area of Liberia and are ideal for earth building construction. Generally, the particle distribution for Liberia's soils ranges from 0 %to 76% for gravels; 31% to 98% for sands; 1% to 39% for silts; 1% to 46% for clays; and 0% to 4% for humus (Reed, 1951). Particles distribution data used in this research were generated from soil analysis tests carried out in Western Liberia by James Kazulu of the University of Liberia. The samples analyzed contained a particle size distribution of 46.25% for sands; 18.9% for silts; 32.25% for clays, and 3.25 for humus.

Suitability of Liberia's Soils

This section discusses results of particles analysis of the local Johnson City, Tennessee, earth sample used to simulate Liberia's soils and tests carried out on specimen blocks.

Local Soil Analysis Results

The two different analysis tests carried out on the local Johnson City, Tennessee, earth sample confirmed the classification of the local soil, now considered a Liberia earth sample, as sand-clay with particle size distribution, 46.51% for sands; 18.60% for silts; 32.56% for clays, and 2.33% for humus.

Specimen Blocks Test Results

Results from the test are reported in Figures 8 – 12. Interestingly, all of the figures exhibit the same trends, which show the existence of optimum moisture content for each soil configuration, with or without stabilizer.

Figure 8 is for an unstabilized soil and has a maximum compressive strength of 293.11N/cm² (425.41lbs/in²) at moisture content of 22%.

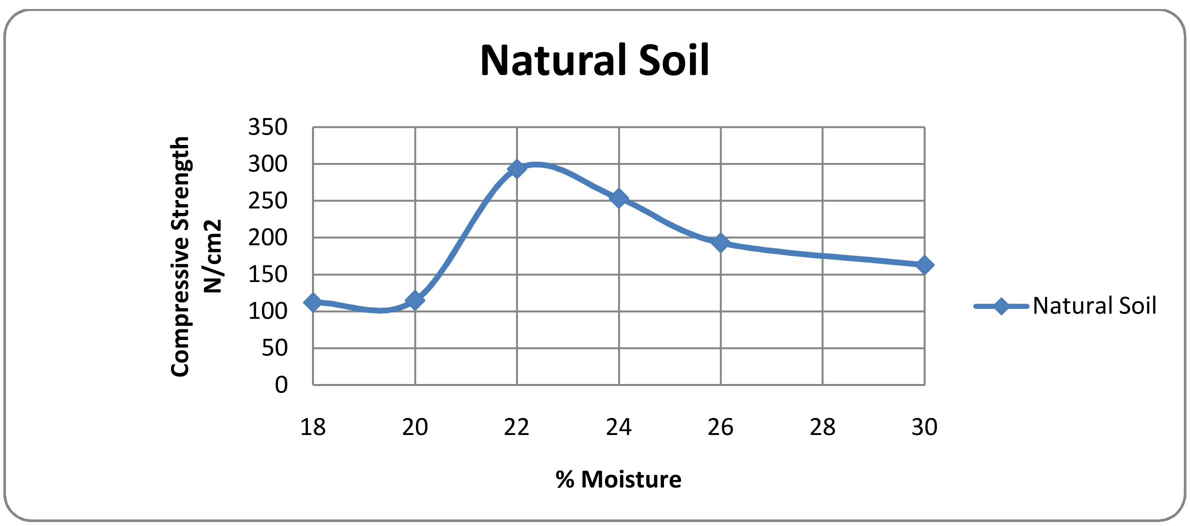

Figure 8. Natural earth - Moisture Vs Stress plot

Figures 9 & 10 are for 5% and 8% of Bentonite added to the soil, respectively. From these figures it is observed that a 5% addition of Bentonite results in an 11.5% increase in compressive strength over unstabilized soil. However, 8% of Bentonite added to the soil produced no notable increase in compressive strength.

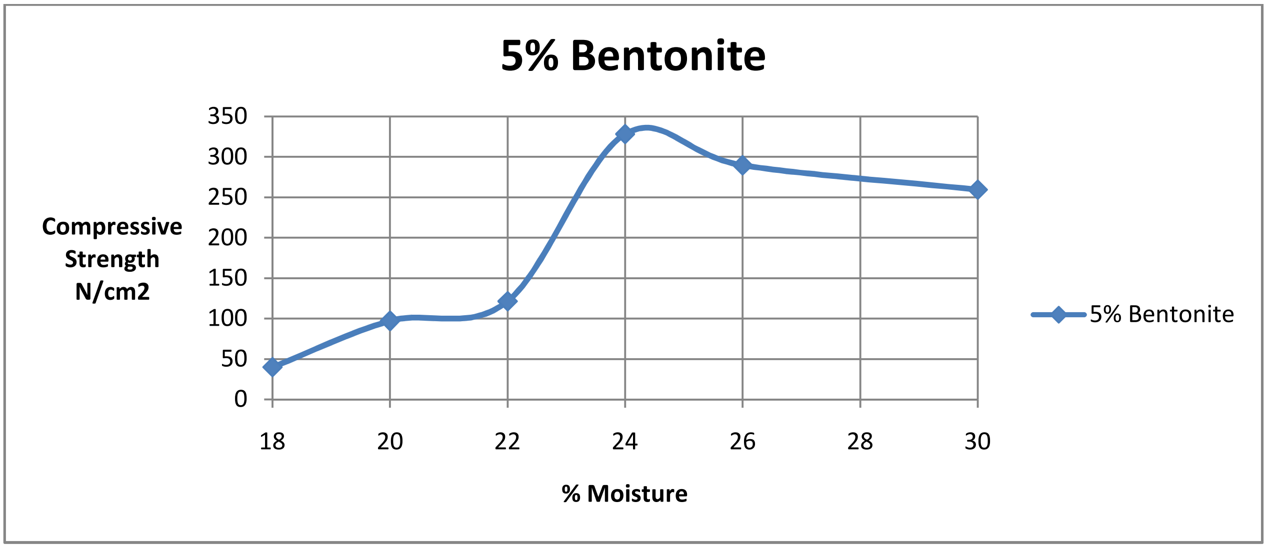

Figure 9. Soil + 5% Bentonite – Moisture Vs Stress Plot

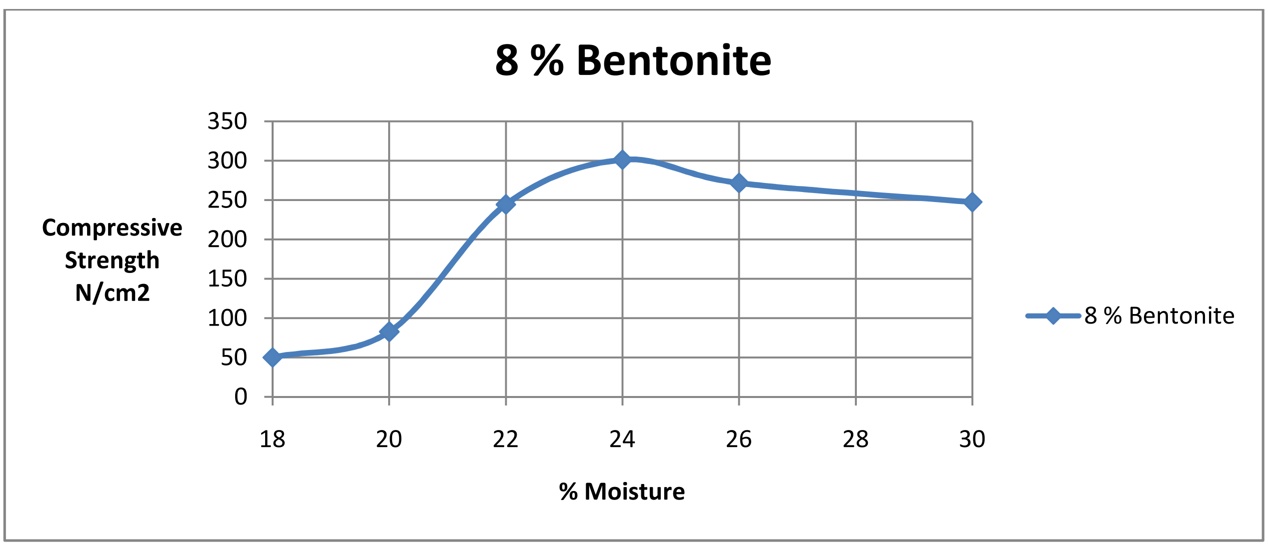

Figure 10. Natural Earth + 8% Bentonite – Moisture Vs Stress Plot

Figures 11 & 12 are for 5% and 8% of cement added to the soil, respectively. From these figures it is observed that a 5% addition of cement results in 95% increase in compressive strength over unstabilized soil. For 8% addition of cement to the soil, the result is an increase of 137% in compressive strength.

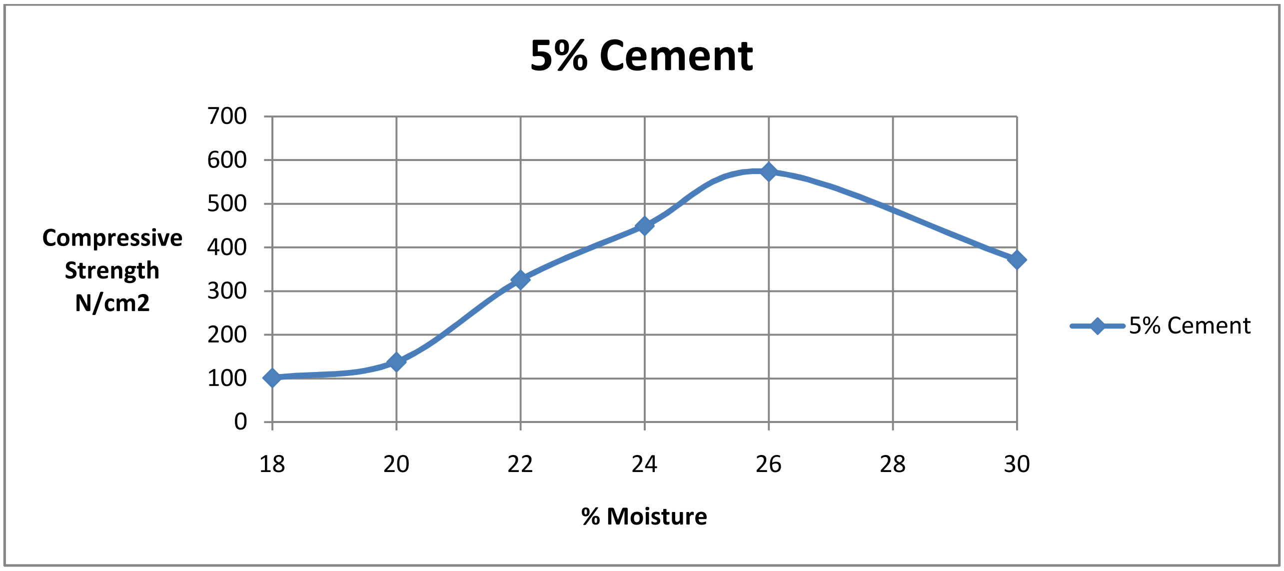

Figure 11. natural earth + 5% cement – Moisture Vs Stress Plot

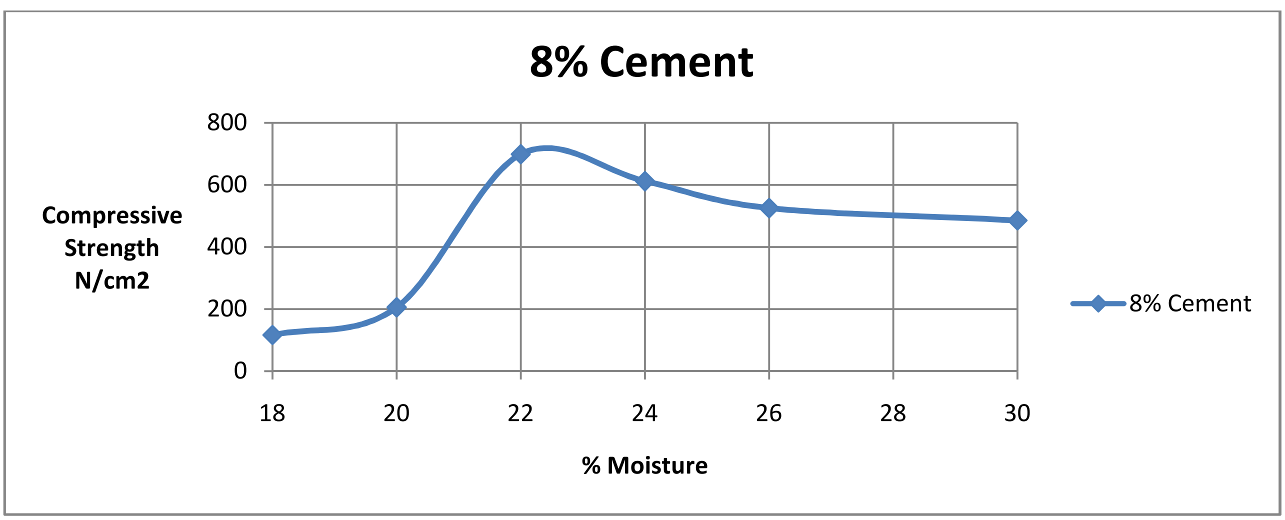

Figure 12. Natural Earth + 8% Cement – Moisture Vs Stress Plot

These results, averages of which are summarized in Table 9, are also graphically shown in Figure 13 to enhance a visual interpretation of the relationship between the configurations.

Table 9

Summary of block test data

Moisture content (%)	Natural soil (NS)	NS + 5% Bentonite	NS + 8% Bentonite	NS + 5% Cement	NS + 8% Cement
	Average compressive stress (N/cm²)				
18	111.20	39.87	50.07	101.38	115.83
20	114.90	97.13	82.65	137.55	204.85
22	293.11	121.26	244.33	325.78	698.61
24	253.40	328.20	301.04	449.46	611.74
26	193.05	289.58	271.48	573.12	524.87
30	162.89	259.42	247.34	371.63	485.14

Conversion: $lb/in^2 = N/cm^2 /0.689$ (for example, strength = 293.11/0.689 = 425.41 lb/in^2)

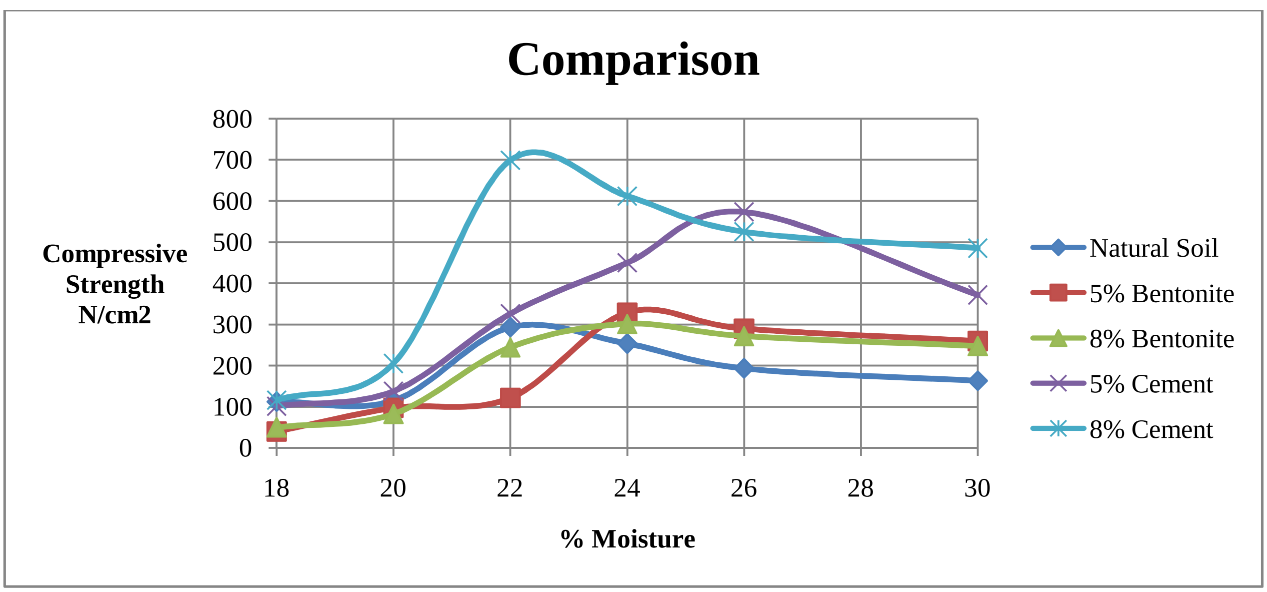

Figure13. Combined Results of the Various Configurations

A summary of the optimum moisture content and average compressive stress for each configuration is given in Table 10.

Table 10

Summary of Optimum Moisture and Average Compressive Stress

	Configurations and Optimum average compressive Strengths									
Optimum Moisture content (%)	Natural Soil (NS)		NS + 5% Bentonite		NS + 8% Bentonite		NS + 5% cement		NS + 8% Cement	
	N/cm²	lb/in²	N/cm²	lb/in²	N/cm²	lb/in²	N/cm²	lb/in²	N/cm²	lb/in²
22	293.11	425.41								
24			328.20	476.34						
24					301.04	436.89				
26							573.12	831.81		
24									611.74 .	887. 87

Structural and Cost Evaluation Results

Table 10 contains averages of the optimum compressive strengths obtained from testing the specimen blocks. A review of the table shows that natural earth with no stabilizer added has the lowest compressive strength at 293.11N/cm². This value can be more than doubled, to 612N/cm², by adding 8% cement if needed. However, the goal here is to determine whether blocks made from the natural soil with no stabilizer added are adequate for building purposes. Therefore the compressive stress obtained from testing blocks made from the natural “Liberian” soil with no stabilizer added, was compared with the highest possible compressive stress expected from the single-story residential example house. The example house is detailed in Appendix B. From Appendix B, the compressive stress that can result from the heaviest possible roof over the walls of a single-story residential building is 9.42N/cm². That is for the example house; the native Liberia soil is suitable and needs no enhancement with stabilizer (cement).

While it has been shown that native Liberian soil does not need to be enhanced with stabilizer for the single-story residential example house, doing so does not increase the overall cost of the project by any significant amount. Referring to the example house in appendix B, the cost of the blocks without stabilizer is $433.05. This amount is increased by 94.4% ($408.72) when 5% stabilizer (cement) is added to the soil. However, the 94.4% increase only affects the cost of the blocks, not the overall cost of the project. Comparing this increase to a project costing between $10,000.00 and $15,000.00, the overall cost will only increase by between 4% and 3%, an acceptable tradeoff for higher compressive strength (22.92N/cm²), hence a durable and weather resistant building.

CHAPTER 5

DISCUSSION

Statement of Liberia's Soils Suitability

Based on findings from data collection and analysis, it is concluded that the Latosols of Liberia, which occupies about 75% of the country's total land space, is suitable for earth-building purposes. According to the results of tests conducted on the simulated Liberia's earth sample, soils of Liberia meet both texture and structural requirements for earth building purposes.

It is shown that the mechanical properties of the Latosols of Liberia can be enhanced through the use of chemical stabilizer. The results revealed when cement is added to the soil, the compressive strength is increased 1.9 – 2.4 times depending upon cement concentration. The addition of Bentonite has mixed results; from 5% added, only approximately 12% increase in the compressive strength over natural soil was observed. The increase in strength was even lower (about 2.7%) for 8% Bentonite added to the soil.

The performance of Bentonite in the soil seems to suggest that the soil is sufficient in clay and does not require a clay supplement such as Bentonite. Also the performance of cement further confirms that it is the best choice where chemical stabilizer is needed. In the case of Liberia, this finding is particularly important because cement is the most commonly available chemical stabilizer currently on the Liberian market.

Structural and Cost Implications

From the assessment of the example house mentioned earlier, three facts were revealed:

1. Blocks made from Liberia soils are structurally capable to withstand more compressive stress than the stress imposed by the worst case scenario. Though single-story residential buildings in

Liberia do not carry concrete roof, blocks made from Liberian soils under strict adherence to earth building principles and requirements, can carry a load heavier than that of a 10.16 cm (4”) thick concrete slab. The roof of the example house only imposes a compressive stress of 9.42N/ cm^2 (13.67lbs/in^2), which is less than the compressive strength of the blocks with which the walls are built (293.11/25 =11N/cm^2 or 17.02lbs/in^2) when modified by a safety coefficient of 25.

2. The stress bearing capacity of the block increases by 12% by adding 5% Bentonite and 95% by adding 5% cement to the soil. But from the stress assessment of the example building, a single-story residential building having a roof not heavier than a 10.16cm (4”) thick concrete slab does not require the addition of chemical stabilizer (cement) to the soil.

3. From the cost analysis shown in appendix B, the cost for the production of the blocks for the example house, which measures 6.1m x 12.2 m (20’ x40’) in area and a height of 2.44m (8ft.), will increase by 18.9% for every 1% of stabilizer added to the soil. Increasing the cost to produce the blocks by this much may not seem justified, as the structural capacity of the blocks with no stabilizer (cement) added has been shown to be adequate for the example house. However, doing so does not increase the overall cost of the building by any significant amount, while almost doubling the strength of the blocks and therefore the durability of the house.

Why Liberia Stands to Benefit

In addition to the soils being suitable, the country stands to benefit should the government welcome the technology and give it the recognition it deserves. There are several reasons why the country could benefit, but preference is given to the following three.

The Technology is Highly Developed and Evolving

Since its revival, earth-building technology has developed and its application in home construction has continued to evolve in proving its scientific significance. Researchers, the business community and builders have developed useful knowledge, which in turn has made the technology competitive to other construction technologies. The use of earth as building material meets scientific requirements for product quality control from identification, extraction, and production to quality assessment of the finished product. The standardization of procedures and tests, together with experience of earth builders, has helped to establish architectural and engineering principles and practices as guide for contractors and self builders, (Rigassi & CRATerre, 1985).

Improvements in the earth building industry are equally attracting investors and international donors around the world. Liberia stands to attract some of these investors and donors, particularly the United Nations in its low housing program for developing countries, should the government formally recognize the practice, make it a part of the country's building code and employ it in the reconstruction process. Adapting the technology will also impact the country environmentally; for example it will reduce the rate of beach sand mining for sand-cement type of construction, an operation that has continued to post erosion threats to the country's cities and towns along the sea coast.

Role the Technology Plays in Development

Establishing production sites, whether on a small scale or as big industries, relate directly to job creation. Using earth material for social housing programs, for education and medical facilities, and for administrative buildings, contributes to growth. Encouraging earth building is part of development strategies for the public and private sectors that stress the need for training and new enterprise, thus contributing to economic and social development (Rigassi & CRATerre, 1985). The promotion of the use of earth as building material in Liberia not only have the potential to encourage development growth and improve the country's employment rate, it also offers the opportunity for more people to own homes without having to spent needless amount of money. For example, the price of 15.2cm (6”) cement block (the most used for building in Liberia) is roughly 9 to 6 times higher than that of adobe block, excluding transportation costs. This is based on the author’s experience as a native of Liberia where the cost of adobe varies between \$0.10 and \$0.15 per block versus \$0.85 per cement block.

Social Acceptability of the Technology

The technology level to which earth is now being used as building material has made it a matter of choice over other materials such as sand-cement blocks or fire bricks. This improved use has inspired decision makers, builders and end-users. Such an improvement, together with government’s encouragement, will build the confident level, hence the desire of more people to use the material, the result of which will be to accelerate the reconstruction process.

Future Work and Recommendations

Future Work

During the research, particularly the specimen blocks production and testing periods, two important observations that require future consideration were made.

1. Specimen blocks were produced and tested for compressive strength following 14 days of curing. Their strengths were observed to increase with increase in moisture content until optimum moisture content was achieved. However, it is not known by what rate of increase the blocks reached the 14 days’ optimum strength, neither is it known whether the strength of the blocks would have increased or decreased had they been allowed to cure for less or more than 14 days.

2. The strength of the blocks increased by 12% when 5% Bentonite was added to the soil, but no noticeable increase in compressive strength was observed when 8% Bentonite was added. What could have caused this unusual rate of change?

3. The addition of cement to the soil improves its resistance to moisture intrusion. What reasonable concentration of cement added to the soil will yield optimum result?

Recommendations

1. That future study should be carried out based on data, grain size analysis, compressive strength, etc, using Liberian indigenous soil samples collected from different locations, for example, North, South, etc., of Liberia. This will be the basis for standardizing the average load bearing capacity of Liberia soils for design purposes.

2. That the Government of Liberia partner with international organizations such as the United Nations, etc, for the construction of test buildings for public exhibition. Such buildings built using the unstabilized-compressed and rammed earth techniques of earth building construction, could be single-story residential apartment complex for low income individuals and public buildings such as schools, clinics, etc. In this way the public will see for itself the potential earth has to be used to construct decent, durable, and habitable buildings.

3. That the Government of Liberia engages in a bench mark study for the possible establishment of a vocational training and research institution specialized in earth building construction to research the local soils and train individuals in various aspects of earth building technology.

4. That a special commission comprising of architects, engineers, financial institutions, and entrepreneurs be established to guarantee the entrenchment and the professional practice of earth building technology in Liberia.

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APPENDIXES

APPENDIX A

Detail of Block Test Data

Table 11

Detail of Block Test Data

General data: Volume (V) = 541.02 cm³ (33.12 in³); Area (A) = 71cm² (11.04 in²)				
Category and Description	Compressive Force		Compressive Strength	
Description + Moisture Content	Newton= lb-force x 4.448	Force (Lbs)	N/cm² = lb/in²x0.689	(L b/in²)
1 - 1 Natural soil + 18%	7,924.11	1,781.5	111.20	161.37
1 – 2 Natural soil + 20%	8,188.77	1,841	114.90	166.76
1 – 3 Natural soil + 22%	20,890.79	4,696.67	293.11	425.42
1 – 4 Natural soil + 24%	18,058.88	4,060	253.40	367.75
1 – 5 Natural soil + 26%	13,759.13	3,093.33	193.05	280.19
1 – 6 Natural soil + 30%	11,609.28	2610	162.89	236.41
2 – 1 soil + 5% Bentonite + 18%	2,837.82	638	39.82	57.79
2 – 2 soil + 5% Bentonite + 20%	6,922.56	1,556.33	97.13	140.97
2 – 3 Soil + 5% Bentonite + 22%	8642.46	1,943	121.26	176
2 – 4 Soil + 5% Bentonite + 24%	23,390.56	5,258.67	328.20	476.33
2 – 5 Soil + 5% Bentonite + 26%	20638.72	4,640	289.58	420.29
2 – 6 Soil + 5% Bentonite + 30%	18,488.87	4,156.67	259.42	376.51
3 – 1 Soil + 8% Bentonite + 18%	3,568.76	802.33	50.07	72.67
3 – 2 Soil + 8% Bentonite + 20%	5,890.62	1,324.33	82.65	119.96

Table 11 continues				
3 – 3 Soil + 8% Bentonite + 22%	17,413.92	3,915	244.33	354.62
3 – 4 Soil + 8% Bentonite + 24%	21,498.65	4,833.33	301.64	437.80
3 – 5 Soil + 8% Bentonite + 26%	19,348.80	4350	271.48	394.02
3 – 6 Soil + 8% Bentonite + 30%	17,628.90	3,963.33	247.34	358.99
4 – 1 Soil + 5% Cement + 18%	4,944.71	1,111.67	101.38	100.69
4 – 2 Soil + 5% Cement + 20%	9,803.40	2,204	137.55	199.64
4 – 3 Soil + 5% Cement + 22%	23,218.56	5,220	325.78	472.83
4 – 4 Soil + 5% Cement + 24%	32,033.03	7,201.67	449.46	652.33
4 – 5 Soil + 5% Cement + 26%	40,847.45	9,183.33	573.12	831.82
4 – 6 Soil + 5% Cement + 30%	26,486.37	5,954.67	371.63	539.37
5 – 1 Soil + 8% Cement + 18%	827.33	1,856	115.83	168.12
5 – 2 Soil + 8% Cement + 20%	13,716.16	3,083.67	204.85	297.32
5 – 3 Soil + 8% Cement + 22%	49,790.91	11,194	698.61	1,013.95
5 – 4 Soil + 8% Cement + 24%	43,599.30	9,802	611.74	887.86
5 – 5 Soil + 8% Cement + 26%	37,407.68	8,410	524.87	761.78
5 – 6 Soil + 8% Cement + 30%	34,575.77	7,773.33	485.14	704.12

Note: To get N/cm^2, multiply lb/in^2 by 0.689 and to get kg, divide pound by 2.205.
For example, 704.12 lbs/in^2 = 704.12 lbs/in^2 x .689 $N/cm^2/lb/in^2$ = 185.14 N/cm^2

APPENDIX B

Example House for Structural and Analysis

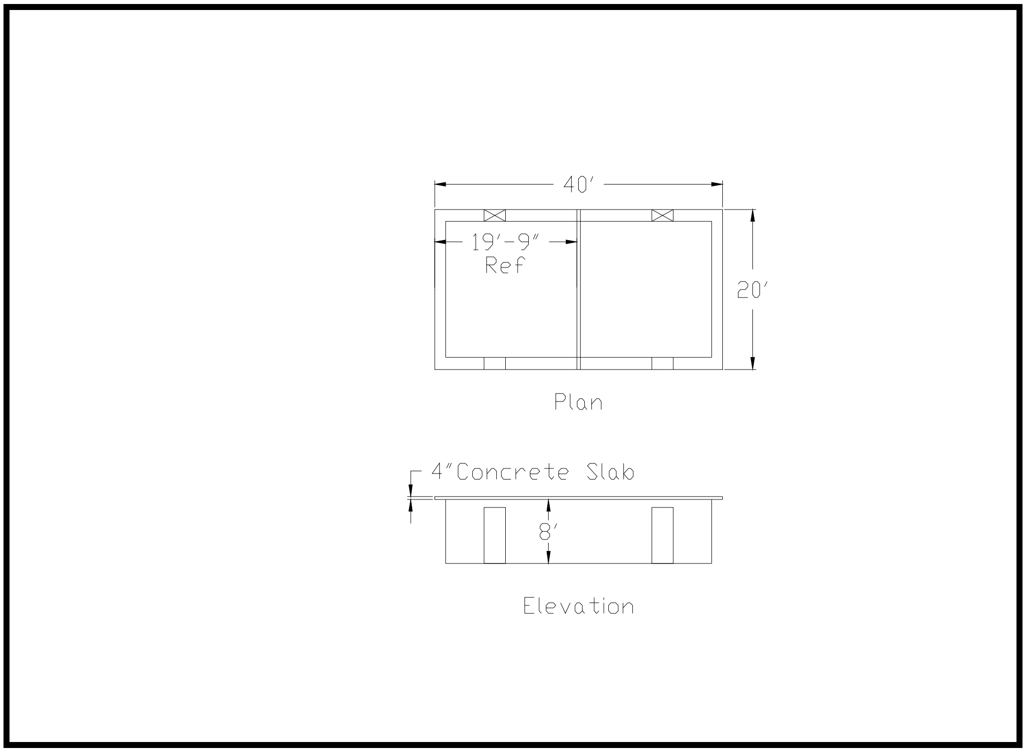

Figure 14. Example House

Example House - Structural and Cost Benefit Analysis

Requirement for a Typical Building of size 6.01m x 12.20m

Structural calculations. To determine the structural suitability of blocks made from Liberian soils, the middle wall of an example house (plan and elevation shown in Figure 14) is considered. For the purpose of this analysis, a 10.16cm (4") thick reinforced concrete slab is taken as the roof of the example building, which measures 6.1m x 12.2m (20ft x 40ft.) in area and has a wall height of 2.44m (8ft.) Given the density of reinforced concrete as 2400kg/m³ (150lb/ft³), the force from the slab on the middle wall can be computed as follows:

Force = volume of slab x density of concrete x acceleration due to gravity

= (0.10 x 6.01 x 6.01) m^3 x 2,400kg/m^3x 9.81m/s^2

= 87,607.224kg-m/s^2 or 87,607.22N /6.1

=14,361.84N/m

Therefore stress imposed on the wall (width = 0.1524m) = (14,361.84N/m / 0.1524m

= 94,237.80 N/m^2

= 9.42N/cm^2 (13.67lb/in^2)

For single-story building, a strength coefficient of 25 is desired.

Therefore design strength = Average compressive strength divided by strength coefficient

= 293.11N/cm^2/25

= 11.72 N/cm^2 (17.02 lbs/in^2)

Comparing applied stress (9.42N/cm^2) to design strength (11.72 N/cm^2), design strength is greater. Therefore the wall is capable of carrying the load imposed on it.

Cost Analysis

Quantity of blocks required. Total running wall length 41.76m (137ft.)

For a typical block size of (w x h x l) = 0.152m x 0.152m x 0.254m (6”. x 6”x 10”), number of blocks required for one course along the running length = 41.76m/0.254m = 164 blocks.

Considering a wall height of 2.44m (8ft.) high built with blocks 15.24cm (6”) thick, number of courses required is given by height of wall divided by the thickness of one block.

That is number of courses = 2.44m/0.152m = 16 courses.

Required blocks = number for one course multiply by number of courses

= 164 x 16 = 2,624 blocks.

Add for contingency, 10% of required blocks.

Therefore total blocks needed = 0.1 x 2,624 + 2624 = 2,887 blocks.

Material required for producing the blocks.

Volume of one block = 0.152m x 0.152m x 0.254m = 0.0059m^3 (0.20825ft^3)

Total volume of earth material required = 0.0059 x 2,887 =17.03m^3 (601.22ft^3)

Assuming that the earth material has a density of 1500kg/m^3, its

Mass = 17.03m^3 x 1500kg/m^3 = 25,545kg (56,199lbs)

For a degree of stabilization = 5, determine the mass (weight) of stabilizer required using Equation (4),

$V_E = M_C \times 100 / \rho_E \times C$ or $M_C = (\rho_E \times C \times V_E) / 100 = (1{,}500 kg/m^3 \times 5 \times 17.03 m^3)/100$

$= 1{,}277.25 kg$ (2809.95lb)

For the purpose of this cost analysis, only Portland cement is considered, because it is the only known chemical stabilizer sold in Liberia. Therefore in the following steps the cost added to the cost of the blocks by adding 1,277.25kg (2,809.95lb) of cement to the earth material is determined.

The author is a native of Liberia and knows from experience that the cost to produce one adobe block varies from $ 0.10 to $ 0.15, depending on conditions such as crew men's transportation, feeding, etc. For the purpose of this analysis, a unit production cost of $0.15 is assumed. Also the author knows from experience the retail price of Portland cement to fluctuate between $ 12.00 and $ 15.00 per sack. Therefore a unit price of $ 13.50 for one 42kg (94lb) sack of cement is considered for this analysis.

Considering the cost for a 42kg sack, the price per kilogram cement is given by $13.5/42kg = $0.32/kg. Therefore the cost added by adding cement to the soil to produce the blocks is given by 1,277.25kg x $ 0.32/kg = $ 408.72 and the cost for the blocks without adding cement is given by $0.15/block x 2,887 blocks = $ 433.05. The total cost for the blocks when cement is added is given by

Cost of blocks without cement + cost of cement = $(433.05 + 408.72) = $ 841.77

Percentage increase is given by $408.72 x 100/$433.05 = 94.4% for 5% added stabilizer (cement). However, the 94.4% cost increase only affects the blocks component of the entire project. The increase on the overall cost of the entire project by adding 5% stabilizer (cement) to the soil is negligible considering the cost-benefit. For example, adding 5% stabilizer (cement) to produce the blocks for a modest house costing between $10,000.00 and $15,000.00 will only increase the cost of the entire project by between 4% and 3%. For such a small increase, the compressive strength of the soil almost doubles, which is an acceptable tradeoff if higher compressive strengths are necessary. In addition, the increase in compressive strength of the blocks reduces the vulnerability of the walls to excessive moisture and natural weathering effect.

APPENDIX C

Soil Identification Guide

Figure 15 is the graphical representation of identifying a soil using its PI and LL values.

<table>
<tr><td></td><td colspan="9">Value (%)</td></tr>
<tr><td></td><td>0-5</td><td>5-10</td><td>10-15</td><td>15-20</td><td>20-25</td><td>25-30</td><td>30-40</td><td>40-50</td><td>50 +</td></tr>
<tr><td rowspan="2">Sandy</td><td colspan="2">PI</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">LL</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Silty</td><td></td><td colspan="4">PI</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="4">LL</td><td></td></tr>
<tr><td rowspan="2">Clayey</td><td></td><td></td><td></td><td></td><td colspan="5">PI</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">LL</td></tr>
</table>

Figure 15. Soil Identification with Known Plasticity Index (PI) and Liquid Limit (LL)

APPENDIX D

Selective Pictures - Specimen Blocks Production

Figure 16. (a) Apparatus and Produced Blocks

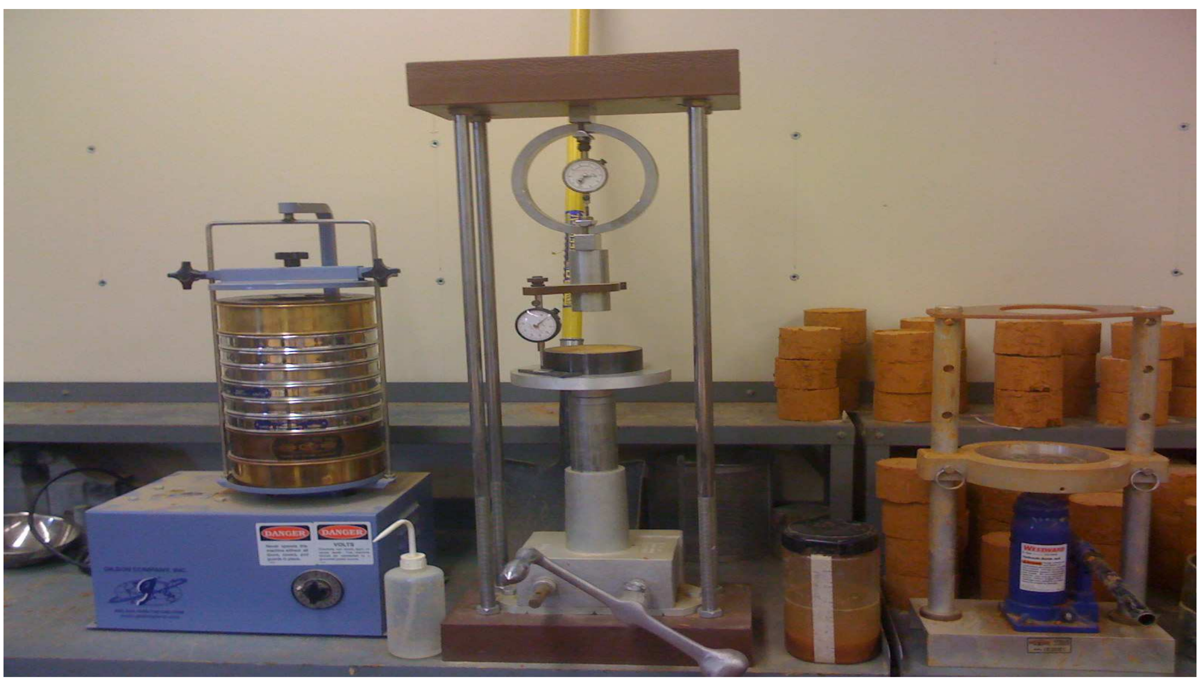

Figure 16. (b) Apparatus and Produced Blocks

APPENDIX E

Full Report on Soil Data from Liberia

Table 12

Full Report on Soil Data from Liberia

Soil analysis results			**(Liberia -Bomi Hills Agriculture Project, 2008)**								
Site 1	Depth **Inches**	**ph (H2O)**	**pH (KCl)**	**Corg**	**Humus (estimated) %**	**Clay %**	**Silt %**	**Sand %**	**EC mg/l**	**EC microS/cm**	
1.1	0-7	5.7	4.5		3.5						
1.2	7-15	5.8	4.5		3.5	24.7	19.6	52.2			
1.3	15-25		4.6		2.5						
1.4	25-40	6.2	4.6		<0.5	42.2	19.6	37.7			
Site 2											
2.1	0-7	5.8	4.6		3.5	33.2	23.6	39.7			
2.2	7-18				3						
2.3	18-25	5.6	4.5		2.5						
2.4	25-30				<2	45.4	21.5	31.1			
2.5	30-45	5.7	4.6		<1						
Site 3											
3.1	0-5	6.1	4.6		3.5	27.6	19.2	49.8			
3.2	5-18	5.8	4.7		3.5						
3.3	18-40	5.7	4.6		<0.5	35.5	16.1	47.9			
3.4	40-100	6.1	4.9		<0.5						
Site 4											
4.1	0-7				4				18	40	(
4.2	7-20	5.8	5		4	22.9	15.4	57.7			
4.3	20-30				3						
4.4	30-40	5.9	5		2.5	27.3	16.2	53.9			
4.5	40-90	6.2	5.1		<0.5				5	11	(
water									13	27	
dest H2O									2	4	

Source contact: Dr. James Kazulu, College of Agriculture, University of Liberia

APPENDIX F

Pictorial Account of Earth-Buildings of Different Sizes, Levels and Shapes

Pictures shown in Figure 14 are images of buildings built from earth materials. From all indications these buildings meet every requirement a building must have for habitation. More information is available at http://www.earth-auroville.com (Project – Case study)

Figure 17. Picture of earth buildings

VITA

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